

Prominent Polarized Flares of the Blazars AO 0235+164 and PKS 1510–089

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Abstract

We report on multi-band photometric and polarimetric observations of the blazars AO 0235+164 and PKS 1510–089. These two blazars were active in 2008 and 2009, respectively. In these active states, prominent short flares were observed in both objects, having amplitudes of > 1 mag within 10 d. The $V - J$ color became bluer when the objects were brighter in these flares. On the other hand, the color of PKS 1510–089 exhibited a trend that it became redder when it was brighter, except for its prominent flare. This redder-when-brighter trend can be explained by the strong contribution of thermal emission from an accretion disk. The polarization degree increased at the flares, and reached $> 25\%$ at the maxima. We compare these flares in AO 0235+164 and PKS 1510–089 with other short flares which were detected by our monitoring of 41 blazars. Those two flares had one of the largest variation amplitudes in both flux and polarization degree. Furthermore, we found a significant positive correlation between the amplitudes of the flux and polarization degree in the short flares. It indicates that the short flares originate from the region where the magnetic field is aligned.

Key words: BL Lacertae Objects: individual: AO 0235+164, PKS 1510–089 — polarization — infrared: general

1. Introduction

Blazars emit nonthermal radiation over a wide frequency range from radio to gamma-ray bands. There are two components in the emission from blazars (Fossati et al., 1998). The low energy component from radio to optical or X-ray bands is attributed to synchrotron radiation emitted by relativistic electrons in jets. The high energy component is likely to be inverse-Compton scattering radiation. The source of its seed photons has not been identified yet: they may come from the synchrotron radiation (e.g. Jones, O’dell & Stein 1974; Marscher & Gear 1985) or have external origin (e.g. Dermer & Schlickeiser 1993; Sikora, Begelman & Rees 1994).

The synchrotron emission from blazars is occasionally highly polarized in the optical band (Angel & Stockman 1980). Since the polarization gives us a clue to probe magnetic field of a nonthermal radiation source, observations of temporal variations of the polarization are important for study of the structure of a blazar jet. However, the temporal behavior of the polarization is known to be complex. The polarization varies in an erratic manner in most blazars (e.g. Angel & Stockman 1980). On the other hand, systematic variations have also been reported in several blazars, for example, rotations of the polarization (e.g. Qian et al., 1991; Sillanpää et al., 1993). The origin of the rotations of polarization is still an open ques-

tion; Marscher et al., (2008) have suggested a helical structure of the magnetic field based on a rotation observed in BL Lac. Abdo et al., (2010a) have proposed that a rotation of polarization in 3C 279 indicates a bending of the jet. Jorstad et al., (2007) have reported positive correlations between the total flux, fractional polarization, and polarization position angle in the radio and optical bands in 15 active galactic nuclei.

It has been suggested that the erratic behavior of polarization is due to the composition of several polarization components (Moore et al., 1982). From the data of OJ 287 from 2005 to 2009, Villforth et al., (2010) have reported that its observed polarization behavior could be explained by separating the jet emission into two components: an optical polarization core and chaotic jet emission. Uemura et al., (2010) have separated a long-term trend from observed temporal variations of polarization in blazars using a Bayesian approach.

AO 0235+164 is one of the most famous blazars, showing violent variability whose amplitude is larger than 1 mag (e.g. Rieke et al., 1976). Its spectrum shows two absorption-line systems at $z = 0.94$ and $z = 0.524$. The former has been considered as that of AO 0235+164, and the latter is probably attributed to a foreground galaxy (Roberts et al., 1976; Burbidge et al., 1976). The object experienced large amplitude outbursts in past. Radio outbursts repeated quasi-regularly with a periodicity of ~ 5.7

years (Raiteri et al., 2001). The object is highly polarized in the optical band, and the polarization parameters also vary violently. The highest polarization degree has been reported to be 43.9 % (Impey, Brand & Tapia 1982).

PKS 1510–089 is a radio-loud, highly polarized quasar at $z = 0.361$. The object is detectable from the radio to gamma-ray bands (e.g. Kataoka et al., 2008; Abdo et al., 2010b). The spectral energy distribution of the object has a bump structure over a synchrotron component in the ultraviolet (UV) band (Singh, Shrader & George 1997; Kataoka et al., 2008). The UV bump is thought to be thermal emission from an accretion disk. Polarization parameters of the object have also been varied. Marscher et al., (2010) reported that the polarization rotated consecutively for 50 ± 10 d.

In the above two blazars, we detected prominent short-term flares with a timescale of ~ 10 d, and found that they were associated with violent variations in polarization. In this paper, we report their light curves, color and polarization variations, and discuss the characteristics in polarization variations of such short-term flares. This paper is arranged as follows: In section 2, we present our observation method and analysis. In section 3, we report the result of the photometric and polarimetric observations of these objects. In section 4, we first describe long-term and short-term variation components indicated by the flux and color variations. Second, we discuss a correlation between the amplitudes of the flux and polarization degree in short-term flares in 41 blazars. The conclusion is drawn in section 5.

2. Observation

We performed monitoring of AO 0235+164 and PKS 1510–089 in the 2008–2009 seasons using TRISPEC attached to the Kanata 1.5-m telescope at Higashi-Hiroshima Observatory. TRISPEC (Triple Range Imager and SPECtrograph) has a CCD and two InSb arrays, which enable photopolarimetric observations in an optical and two NIR bands simultaneously (Watanabe et al., 2005). Unfortunately, the K_S -band readout system of TRISPEC was out of action. Thus, we obtained only V - and J -band data. A unit of the observing sequence consisted of successive exposures at four position angles of a half-wave plate; 0° , 45° , 22.5° and 67.5° . A set of polarization parameters was derived from each set of the four exposures.

The integration time for an exposure depends on the sky condition and the brightness of the objects. Typical integration times were 120 and 108 sec in AO 0235+164, and 150 and 135 sec in PKS 1510–089 in the V and J bands, respectively.

All images were bias-subtracted and flat-fielded, and we performed an aperture photometry with a Java-based package. We performed a differential photometry with comparison stars taken in the same frames of AO 0235+164 and PKS 1510–089. The positions of the comparison stars are R.A.= $02^h38^m32^s.31$, Dec.= $+16^\circ35'59''.7$ and

R.A.= $15^h12^m53^s.19$, Dec.= $-09^\circ03'43''.6$ (J2000.0), respectively. Their magnitudes are $V=12.720$, 13.282 and $J=11.221$, 12.205 , respectively (González–Pérez et al., 2001; Skrutskie et al., 2006). The constancy of the comparison stars was checked by another neighbor stars in the same frames. The position of the check stars are R.A.= $02^h38^m36^s.70$, Dec.= $+16^\circ36'26''.6$ and R.A.= $15^h12^m51^s.64$, Dec.= $-09^\circ05'24''.1$ (J2000.0), respectively. No significant flux variation was observed in the comparison stars over 0.16 and 0.07 mag in the V band during our observation period.

We confirmed that the instrumental polarization was smaller than 0.1 % in the V band using observations of unpolarized standard stars. We, thus, applied no correction for it. The zero point of the polarization angle is corrected for in the equatorial coordinate system (measured from north to east) by observing the polarized stars, HD 19820 and HD 25443 (Wolff, Nordsieck & Nook 1996).

3. Result

3.1. AO 0235+164

We had performed the photopolarimetric monitoring of AO 0235+164 from Aug. 12, 2008 to Feb. 18, 2009. Figure 1 shows the light curve of the object in the V band, $V - J$ color variation, and temporal variations of the polarization parameters in the V band. We also show relative magnitude between the comparison and the check stars. In the top panel of figure 1, the object showed the violent variability. The object had been active for 153 d from JD 2454696 to 2454849, in which it was brighter than $V = 18.0$. The peak flux of the object was $V=15.067 \pm 0.004$ (JD 2454733). The faintest state of the object has been reported at $V \sim 20$ for 32 years from 1975 to 2007 (Raiteri et al., 2001; Raiteri et al., 2005; Raiteri et al., 2006; Raiteri et al., 2008). Thus, the amplitude of the flux variation was about 5 mag. The light curve shows several short flares during the active state. We can see five flares labelled in figure 1 as “A” (from JD 2454720 to 2454742), “B” (from JD 2454747 to 2454758), “C” (from JD 2454785 to 2454801), “D” (from JD 2454803 to 2454815) and “E” (from JD 2454820 to 2454840).

The $V - J$ color was variable in our monitoring period, $\Delta(V - J) \sim 0.5$. In flares “A” and “B”, the color became bluer. The object, thus, showed a bluer-when-brighter trend in these prominent flares. The color also became bluer in JD 2454696, at the onset of the active state when the object was brightened rapidly. On the other hand, no clear bluer-when-brighter trend was associated with flares “C”, “D” and “E”. In the faintest state in JD 2454879, the object was the reddest.

The polarization degree was variable, and distributed from 0 % to ~ 30 %. In JD 2454755, the polarization degree was the highest, 34 ± 2 %. The polarization degree was correlated with the flux in the flares “A” and “B”. The peaks of the polarization degree in the flares “A” and “B” were higher than 25 %. However, the polarization degrees were not high during the flares “C”, “D” and “E”, less

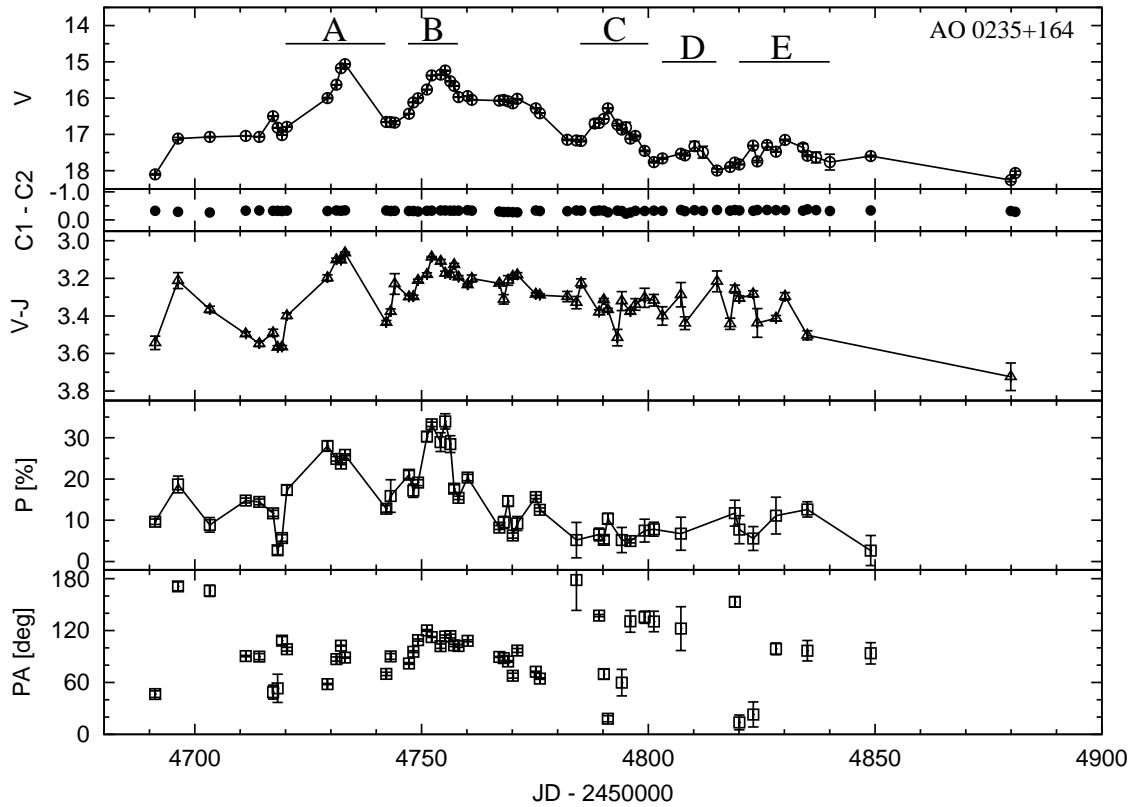


Fig. 1. Light curve of AO 0235+164 in the V band, color variations of $V - J$, temporal variations of the polarization degree (%) and angle (degree). We also show the relative magnitude, C1-C2, between the comparison star (C1) and the check star (C2).

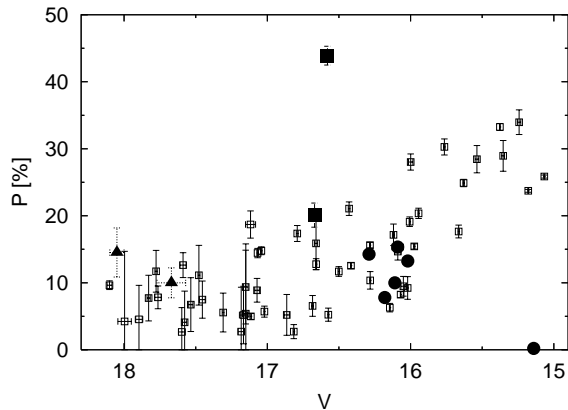


Fig. 2. Correlation between the magnitude and the polarization degree in the V band. Open squares, filled squares, triangles and circles denote the observations with the Kanata telescope, reported by Impey, Brand & Tapia (1982), Mead et al., (1990) and Takalo et al., (1992), respectively.

than 16 %.

Figure 2 shows the correlation between the flux and the polarization degree in the V band. We show our observations by open squares, and the data reported by Impey, Brand & Tapia (1982), Mead et al., (1990) and Takalo et al., (1992) by filled squares, triangles and circles, re-

spectively. The V-band flux was moderately correlated with the polarization degree when the object was brighter than $V = 17$. The flux was uncorrelated with the polarization degree when it was fainter than $V = 17$, while the error of the polarization degree is large in the faint state. A correlation coefficient between the flux and polarization degree was calculated to be $0.74^{+0.09}_{-0.14}$ (95 % confidence interval) in the whole data. In the case of the data brighter than 17 mag., the correlation coefficient was $0.76^{+0.11}_{-0.20}$.

In figure 2, most of the data reported in previous studies were consistent with our data, while there are two exceptions. First, Impey, Brand & Tapia (1982) reported that AO 0235+164 underwent a polarization burst, reaching a polarization degree of 43.9 ± 1.4 % when it was $V = 16.58$. In our data, the object exhibited polarization degrees lower than 19 % around $V = 16.5$. Second, Takalo et al., (1992) reported a low polarization degree of 0.21 % when the object was in a bright state at $V = 15.14$, while our data show high polarization degrees in such a bright state. We discuss the behavior of polarization degree in section 4.2.

Figure 3 shows the light curve (top panel), the temporal variation of the corrected polarization angle (middle panel) and the temporal variations of the polarization in the QU plane (bottom panel) in the V band. We calculated the flux, $\nu F\nu$, with 1.98×10^{-5} erg cm $^{-2}$ s $^{-1}$ at

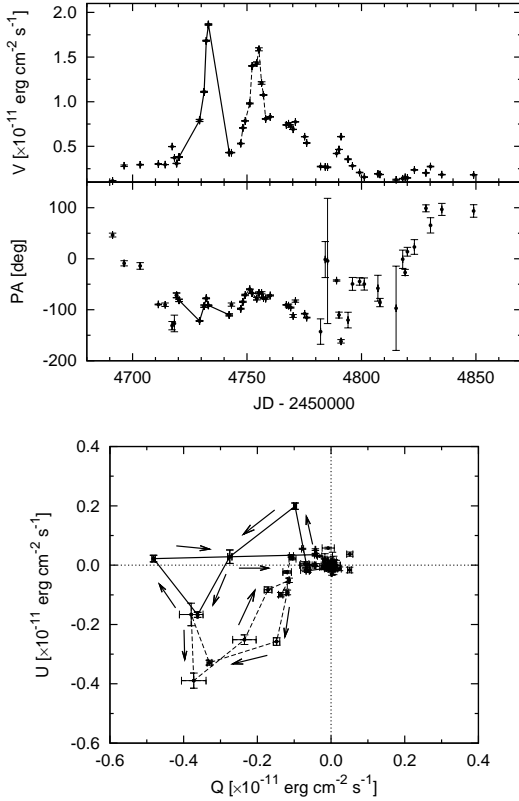


Fig. 3. Top panel: Light curve of AO 0235+164 in the V band. The flux is shown in νF_ν and the unit of the flux is $\text{erg cm}^{-2} \text{s}^{-1}$. The flux was calculated with $1.98 \times 10^{-5} \text{ erg cm}^{-2} \text{s}^{-1}$ at 0 mag in the V band. The solid and dashed lines represent the flares “A” (from JD 2454719 to 2454743) and “B” (from JD 2454747 to 2454761). Middle panel: The temporal variation of the polarization angle in the V band. For details of the correction of the angle, see the text. Bottom panel: The QU plane in the V band. Units of Q and U are $\text{erg cm}^{-2} \text{s}^{-1}$.

0 mag in the V band (Fukugita, Simasaku & Ichikawa 1995). In figure 3, solid and dashed lines indicate the flares “A” and “B”, respectively. The polarization angle shown in the middle panel was corrected to enable the angle to have values over a range of 0° – 180° . In general, the observed polarization angle is defined from 0° to 180° . We corrected the polarization angle assuming that the difference between the polarization angles of the temporal adjacent data should be less than 90° . We defined this difference as $|\Delta PA_n| = |PA_{n+1} - PA_n| - \sqrt{\delta PA_{n+1}^2 + \delta PA_n^2}$, where PA_{n+1} and PA_n were the $n+1$ - and n -th polarization angles and δPA_{n+1} and δPA_n were their errors. If $|\Delta PA_n|$ is smaller than 90° , no correction was performed. If ΔPA_n is smaller than -90° , we add 180° to PA_{n+1} . If ΔPA_n is larger than 90° , we add -180° to PA_{n+1} . As shown in the middle panel, the polarization angles both in the flares “A” and “B” were -122° – -72° and -98° – -60° . The polarization angles of these flares were, hence, different from each other. The polarized flux increased with the flares “A” and “B”, re-

spectively, as can be seen in the bottom panel. Thus, these flares had specific polarization components, which were developed and diminished through the flares. The corrected polarization angle from JD 2454800 to 2454860 seems to rotate gradually. However, it is possible that this rotation was spurious event, because the polarization degree was low and the object was faint during the rotation. The error of the polarization angle was high when the polarization degree was low. We need observations with a higher sampling and smaller errors in order to confirm a long-term rotation event like this.

3.2. PKS 1510–089

We had performed the photopolarimetric monitoring of PKS 1510–089 from Jan. 12 to Jul. 22 in 2009. Figure 4 shows the light curve of PKS 1510–089 in the V band, $V - J$ color variation, and temporal variations of the polarization parameters in the V band. The object has been brightened since JD 2454900, and a peak of the flux was once recorded in JD 2454928. After that, a prominent flare occurred around JD 2454960. We labelled this flare as “F” (from JD 2454954 to 2454966). In this flare, the peak of the flux reached about $V=13.6$ mag in JD 2454961, and the amplitude of the magnitude between the peak and the bottom of the flare in JD 2454954 was $\Delta V=2.5$ mag. After the flare peak, the flux was fallen down to $V=16.2$ mag in JD 2454966. Thus, the flux varied by ten times within 10 d. The flux again rose after this flare, and the flux reached another peak at about $V=15.7$ mag in JD 2454966. After this peak, the flux faded gradually.

The $V - J$ color was about 2.1 in a faint state in JD 2454900. When the object became brighter, the $V - J$ color got redder to 2.5. This “redder-when-brighter” trend was saturated at about $V - J=2.5$. On the other hand, the color during the flare “F” showed a bluer-when-brighter trend. The $V - J$ color reached 1.9 in this flare.

Polarization parameters also varied in the whole observing period. The polarization angle was distributed from 0° to 180° . The polarization degree varied less than 10 % in a faint state from JD 2454844 to 2454911. The polarization degree increased with the flux from JD 2454920, and reached 15 % at the maximum of a small flare in JD 2454928. In the rising phase of the flare “F”, the polarization degree rapidly increased, and reached its peak about 36 % in JD 2454960, in which the flux was still in a rising phase (see the top panel of figure 4). Thus, the peak of the polarization degree was 1 day earlier than that of the flux. In the decay phase of the flux, the polarization degree had already been low, about 13 % in JD 2454962. After the flare, the polarization degree did not vary more than 10 %.

Figure 5 shows a correlation between the flux and polarization degree in the V band in PKS 1510–089. The correlation is quite similar to that observed in AO 0235+164; a positive correlation was clearly seen in a bright state, and in addition, no high polarization was detected when the object were faint. The correlation coefficient was calculated to be $0.70^{+0.12}_{-0.19}$ using the whole data set in

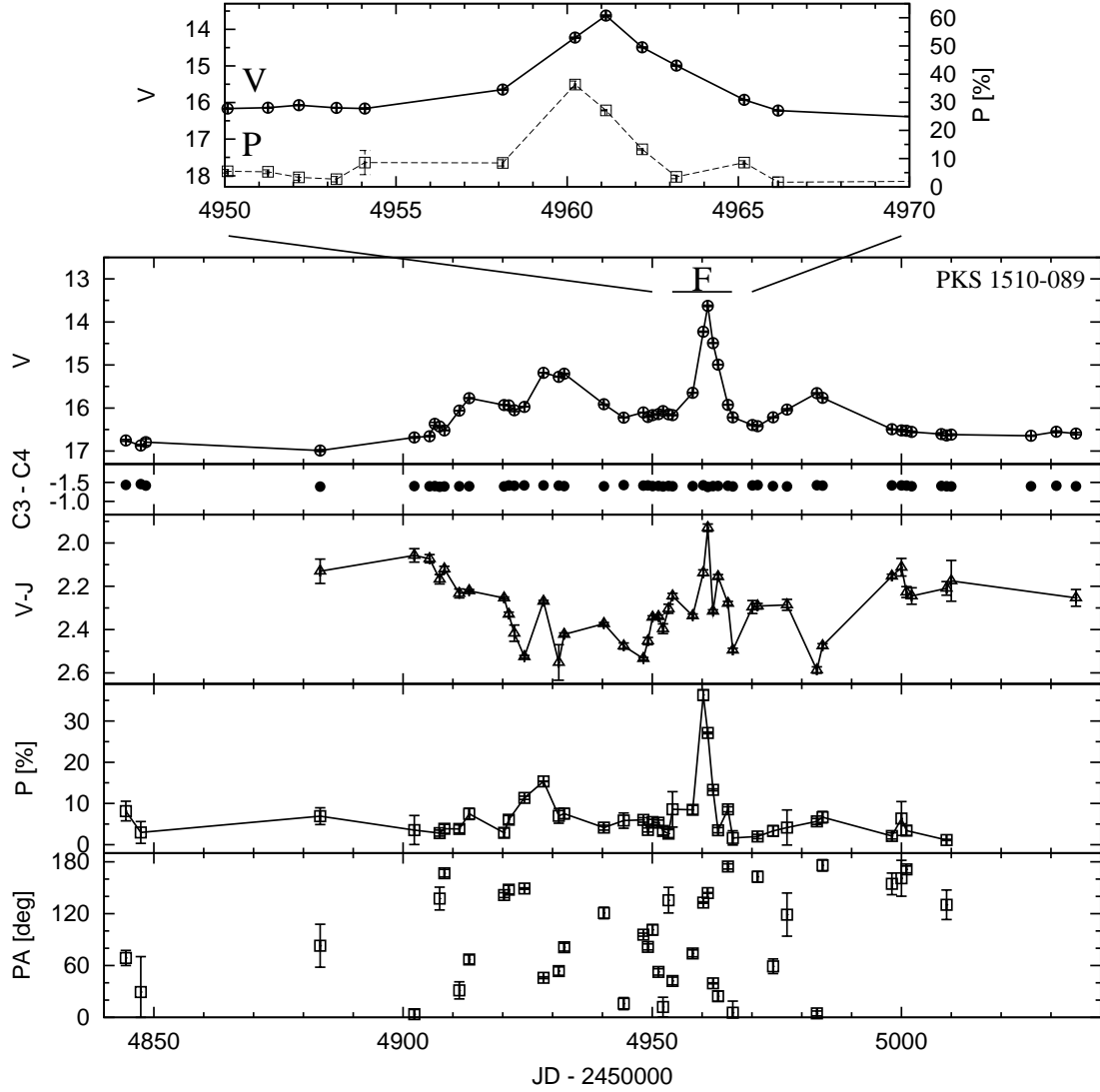


Fig. 4. Light curve of PKS 1510–089 in the V band, color variations of $V - J$, temporal variations of the polarization degree (%) and angle (degree). The top panel shows the enlarged light curve and polarization degree around flare “F”. We also show the relative magnitude, C3-C4, between the comparison star (C3) and the check star (C4).

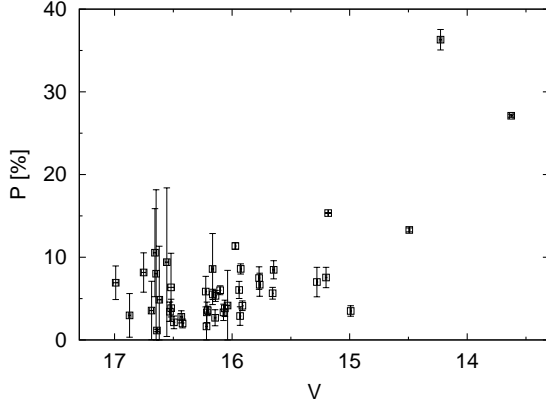


Fig. 5. Correlation between the magnitude and the polarization degree in the V band in PKS 1510–089.

PKS 1510–089. The correlation coefficient using the data brighter than 15.5 mag was $0.77^{+0.19}_{-0.73}$.

Figure 6 shows the light curve (top panel), the corrected polarization angle (middle panel) and the QU plane (bottom panel) of PKS 1510–089 in the V band. The solid line of figure 6 represents the period of the flare “F”. We applied the same correction as described in section 3.2 for the polarization angle. In the middle panel of figure 6, we show corrected polarization angle. As can be seen in this panel, the polarization angle rotated in a positive direction from -40 to 461° from JD 2454907 to 2454950. After a short rotation in a negative direction, it again showed a positive rotation by 173° during flare “F”. The QU plane in the bottom panel of figure 6 also showed the rotation of the polarization during the flare. The polarization parameters, Q and U , were variable dramatically during the flare. Marscher et al., (2010) reported that the polarization angle of this object had rotated for 50 d from JD 2454910. Our observation confirmed this event. The behaviors of polarization angle were different between our data and that of Marscher et al., (2010) during JD 2454951–2454960. This inconsistency is possibly caused by a difference in correction method for the polarization angle or in data sampling rate during this period of time. Therefore, we should be careful in treating the successive rotation trend of the polarization angle.

4. Discussion

4.1. Short- and Long-Term Variation Components

During the flares “A” and “B” of AO 0235+164, the $V-J$ color became bluer. On the other hand, the color did not become bluer clearly during the flares “C”, “D” and “E”. The lack of the color change in the later flares might be partly due to a low signal-to-noise ratio of the photometric data. It is also possible that there was another variation component having a color and a timescale different from those of the flare component. The object was $V \sim 17.0$ just before the onset of the flare “A” (\sim JD 2454719). It was fainter than $V = 17.0$ after the flare

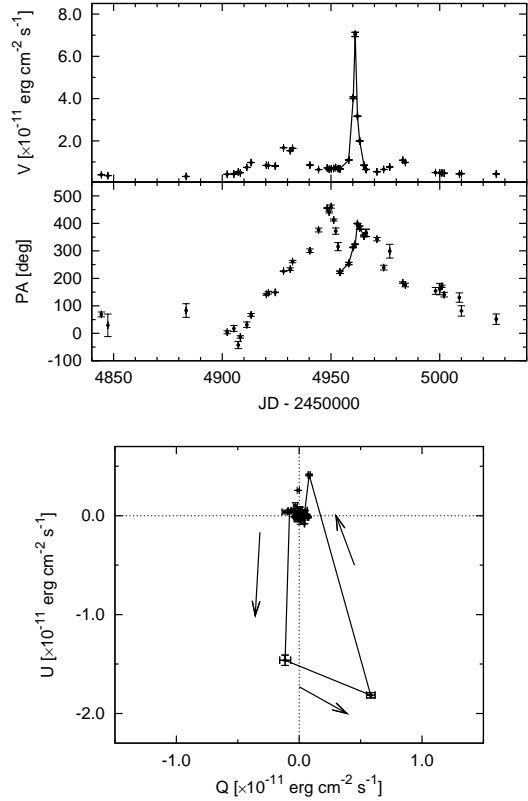


Fig. 6. Top panel: Light curve of PKS 1510–089 in the V band. The flux is shown in $\nu F\nu$ and the unit of the flux is $\text{erg cm}^{-2} \text{s}^{-1}$. The solid line represents the period of the flare “F”. Middle panel: Corrected temporal variation of the polarization angle. For details of the correction, see the text of section 3.2. Bottom panel: The QU plane in the V band. Units of the Q and U are also $\text{erg cm}^{-2} \text{s}^{-1}$.

“C”. If the color follows the bluer-when-brighter trend, the color in the early phase just before the flare “A” should be bluer than that in the late phase after the flare “C”. However, the color in the early phase, $V-J=3.5-3.6$, was redder than that in the late phase, $V-J=3.3-3.5$. This behavior may indicate that there is a variable component which was red in the early phase, then changed to blue in the late phase. The bluer-when-brighter trend was not seen throughout the active state. The light curve suggests that the short-term flares were superimposed on an underlying long-term variation component. The observed color variations can be explained by this two-component scenario; the observed color was a composition of the bluer-when-brighter short-term flares and long-term component having the color variations as mentioned above. Raiteri et al., (2006) have reported that AO 0235+164 possibly showed a gradually reddening trend from 2002 to 2005 although the mean flux were similar in those years. This may also support the presence of the color-variation component on a long timescale.

We tried to separate these two components and to improve the color-magnitude correlation in the short-term flares. We constructed the long-term component using the

linear interpolation of the apparent minima of short-term flares in the light curve. Panel (a) of figure 7 shows the light curves of the observed data, assumed long-term component and the residual short-term component. Panel (b) shows the ratio of the flux between the V and J bands ($\nu F_{\nu V}/\nu F_{\nu J}$) of them. We assumed a long-term component which becomes gradually bluer with time, as shown in the figure. Panel (c) and (d) of figure 8 show the flux–color diagrams between $\nu F_{\nu V}$ and $\nu F_{\nu V}/\nu F_{\nu J}$. The correlation coefficient between $\log(\nu F_{\nu V})$ and $\nu F_{\nu V}/\nu F_{\nu J}$ was calculated to be $0.79^{+0.08}_{-0.11}$ for the separated short-term component, which was higher than the observed one, $0.68^{+0.11}_{-0.15}$. Thus, it demonstrates that the observed color behavior can be explained with the two components, namely the bluer-when-brighter short-term flares and the long-term component.

The $V - J$ color became bluer during the flare “F” of PKS 1510–089. On the other hand, the color during the active state from JD 2454905 to 2454998 exhibited a redder-when-brighter trend. The redder-when-brighter trend has been reported in a few blazars, for example, 3C 454.3 (e.g. Miller et al., 1981). As mentioned before, PKS 1510–089 has a bump structure in the spectral energy distribution in the UV region (Singh, Shrader & George 1997; Kataoka et al., 2008). The redder-when-brighter trend indicates that a synchrotron component, which was redder than the UV bump component, became dominant during the active state. The bluer-when-brighter trend in the flare “F” indicates that the flare component was bluer than the underlying synchrotron component. Thus, we can interpret the observed color behavior as a composition of two synchrotron components; one was the long-term component having a relatively red color, and the other was the short-term flare component having a blue color.

We also tried to separate the short-term flares and long-term component from the observed data of PKS 1510–089. First, we estimated the V - and J -band fluxes of the UV bump component using the inter- and extrapolation of the data from $10^{14.45}$ to $10^{14.6}$ Hz (from 7500 to 10600 Å) reported by Neugebauer, et al. (1979). We subtracted the UV bump component from the observed data, assuming the component was constant over time. After the subtraction of the UV bump component, we separated the short-term and long-term components in a similar way to the case of AO 0235+164. Panel (a) and (b) of figure 8 show the light curve in the V band and $\nu F_{\nu V}/\nu F_{\nu J}$ of the subtracted data, the short-term and long-term components. The $\nu F_{\nu V}/\nu F_{\nu J}$ of the assumed long-term component becomes bluer in its decay phase (JD 2454920–2455000), as that in AO 0235+164. Panel (c), (d) and (e) show the diagrams between $\nu F_{\nu V}$ and $\nu F_{\nu V}/\nu F_{\nu J}$ of the observed, UV-bump subtracted data and short-term component. The correlation coefficients between $\log(\nu F_{\nu V})$ and $\nu F_{\nu V}/\nu F_{\nu J}$ are 0.00 ± 0.30 , $0.68^{+0.15}_{-0.10}$ and $0.88^{+0.05}_{-0.08}$ for the observed, UV-bump subtracted data, and short-term component, respectively. The correlation is improved by assuming the long-term component and separating the short-term flare

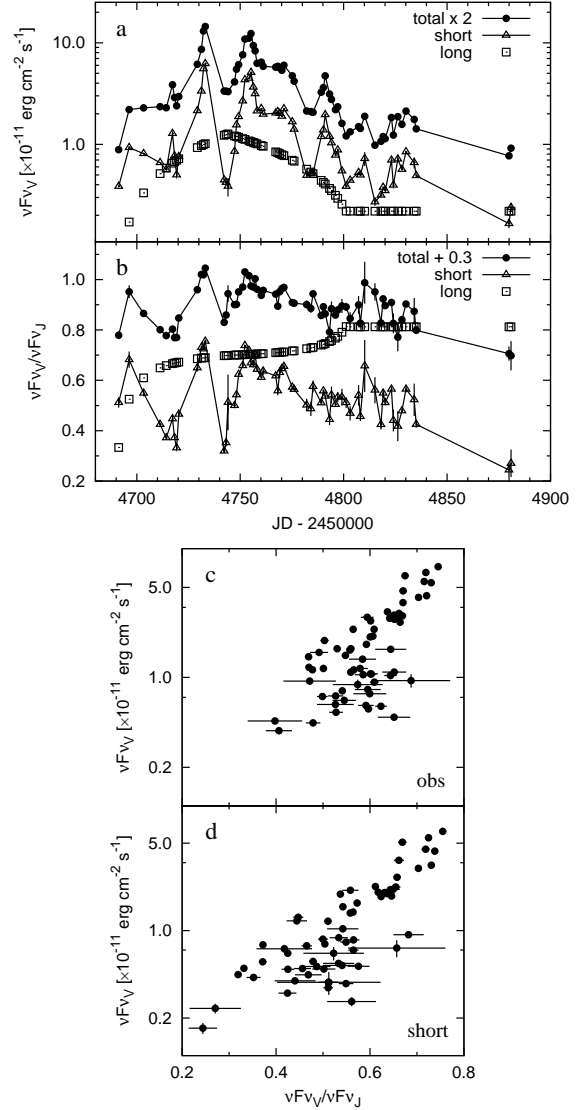


Fig. 7. Light curves, variations of flux ratio and flux–color diagrams in AO 0235+164. Panel (a) shows the light curves of the observed data, the short-term and the long-term components, respectively. The flux is multiplied by a factor for readability. Panel (b) shows the variations of $\nu F_{\nu V}/\nu F_{\nu J}$ of the observed data, the short-term and the long-term components. We add 0.3 to the observed data of $\nu F_{\nu V}/\nu F_{\nu J}$ for readability. The filled circle, triangle and open square in panel (a) and (b) show the observed data, the short-term and long-term components, respectively. Panel (c) and (d) show the flux–color diagrams in the observed data and the short-term component.

component from the observed data.

As mentioned above, the color variations in both AO 0235+164 and PKS 1510–089 can be explained by the two-component scenario; the short-term flare component was superimposed on the long-term one having a different color behavior. Such a two-component picture has been proposed in past studies on blazar variability (e.g. Ghisellini et al., 1997; Villata et al., 2004; Sasada et al., 2010). The timescales of the long-term components in AO 0235+164 and PKS 1510–089 are similar to those in previous studies.

4.2. Correlation between Amplitudes of Flux and Polarization Degree of Flares

In section 3, we reported that there were positive correlations between the flux and polarization degree in both AO 0235+164 and PKS 1510–089. Such correlations between the flux and polarization degree have been reported in other blazars in past studies (e.g. Smith, et al., 1986; Tosti et al., 1998), although the polarization behaviors have generally been reported to be erratic (e.g. Angel & Stockman 1980). We propose that short-term flares on a timescale of 10 d in blazars are associated with increases in polarization degree, with changes of the polarization angle of each flare. If a small flare occurs, this flare is buried by other radiation component, for example the long-term component as mentioned above, and then, the polarization degree is hardly changed. However, a large amplitude flare may not be buried like the flares “A”, “B” and “F”. In this situation, the observed polarization degree should increase during the large flare. In fact, the observed polarization degree during the large flares “A”, “B” and “F” have been changed dramatically.

We investigated the correlation between amplitudes of the flux and polarization degree during flares. We used the photopolarimetric data of 41 blazars which we obtained from 2008 to 2010 (Ikejiri et al., 2009). A full description of the observation and the data reduction will be published in a forthcoming paper. In this paper, we defined the flares and their amplitudes of the flux and polarization degree as described below. First, we defined the peak of a flare as the observation point with the highest flux within ± 10 d. Second, we can calculate the peak-to-valley amplitudes of the flux and polarization degree in this 20 d period.

Figure 9 shows correlation between the amplitudes of the flux and polarization degree of short-term flares selected with the above definition in the V band. There is a positive correlation, and the correlation coefficient is $0.66^{+0.08}_{-0.10}$. The filled circle, triangle and square represent the flares “A”, “B” and “F” of AO 0235+164 and PKS 1510–089, respectively. Those flares are one of the largest flux- and polarization-amplitude flares in our sample (figure 9). On the other hand, the correlation is weak in small flares; there are flares having a relatively large amplitude of flux, but a small amplitude of the polarization degree, and vice versa. This is naturally expected since polarization variations of small flares are readily buried by another variation component in our picture.

Sasada et al., (2008) reported that a microvariation of

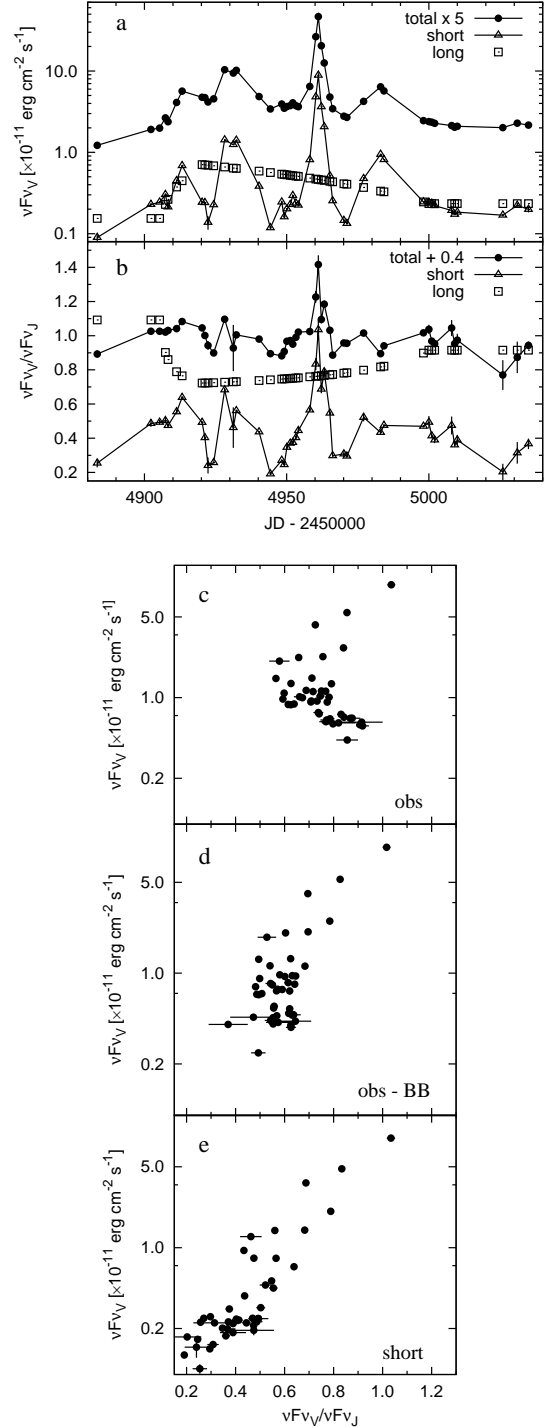


Fig. 8. Light curves, variations of flux ratio and flux-color diagrams in PKS 1510–089. Panel (a) shows the light curves of the UV-bump subtracted data, the short-term and long-term components. The flux is multiplied by a factor 5 for readability. Panel (b) shows the $\nu F_{VV} / \nu F_{VJ}$ of the UV-bump subtracted data, the short-term and the long-term components. We add 0.4 to the subtracted data of $\nu F_{VV} / \nu F_{VJ}$ for readability. Panel (c), (d) and (e) show the flux-color diagrams. In panel (c), we show the diagram of the observed data. In panel (d), we show the diagram of the UV-bump subtracted data. Panel (e) is the diagram of the short-term component.

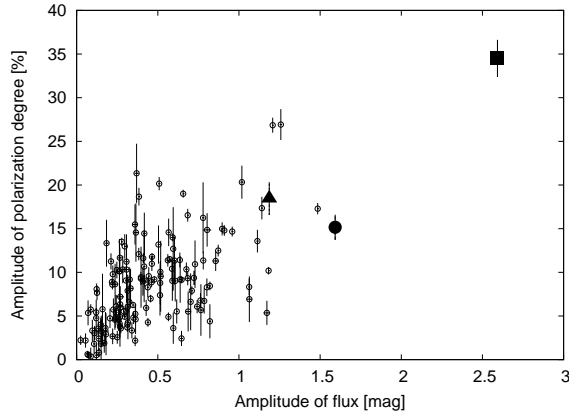


Fig. 9. Correlation between the amplitudes of the flux and polarization degree in short-term flares in blazars in the V band. Definitions of the amplitudes are described in the text. The filled circle, triangle and square represent the flares “A”, “B” and “F”, respectively.

S5 0716+714 had a specific polarization component, and suggested that the microvariation originated from a small and local region where the magnetic field was aligned. Our result indicates that the short-term flares on timescales of 10 d also originate from regions where the magnetic field is aligned.

A part of previous observations of AO 0235+164 is apparently inconsistent with the flux–polarization correlation that we obtained, as mentioned in subsection 3.1. It may suggest that the correlation is not a universal one. Details of variations are, however, unclear for those previous observations; Takalo et al., (1992) reported a quite low polarization degree when the object was bright, while no other observation is available within 40 d of it. Impey, Brand & Tapia (1982) reported a quite high polarization degree when the object was relatively faint, while they reported only two observations. As mentioned in section 1, the observed polarization is possibly a composition of multiple polarization components having different timescales. The presence of short- and long-term components is also indicated by the color behavior in AO 0235+164, as discussed in the last subsection. The exceptions deviating from the correlation between the flux and the polarization degree in figure 2 might be due to the strong contribution of a polarization component having a variation timescale longer than that of the short flares. We need to make continuous photometric and polarimetric monitoring of blazars with higher sampling rate for understanding their polarization behavior more deeply.

5. Conclusion

We performed photometric and polarimetric monitoring of the blazars AO 0235+164 and PKS 1510–089, and observed their flares. The large flares “A”, “B” and “F” exhibited the bluer-when-brighter trends. The $V - J$ color variation of PKS 1510–089 showed the redder-when-brighter trend, except for the period of the

flare “F”. The flux and color variations suggest that there were two variation components having different timescales and colors. There were positive correlations between the flux and polarization degree in both objects. We studied the correlation between the amplitudes of the flux and polarization degree of short flares in 41 blazars. We found that there was a significant positive correlation between them. We propose that the short-term flares on timescales of 10 d originate from a region where the magnetic field is aligned. Observed polarization variations are occasionally erratic probably because polarization variations of small flares are readily buried by another variations having different polarization angles and/or timescales.

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